Force Dynamics as a Design Framework for Mid-Air Musical Instruments

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ABSTRACT
In this paper we adopt the theory of force dynamics in human cognition as a fundamental design principle for the development of mid-air musical interfaces. We argue that this principle can provide more intuitive user experiences when the interface does not provide direct haptic feedback, such as interfaces made with various gesture-tracking technologies. Grounded in five concepts from the theoretical literature on force dynamics in musical cognition, the paper presents a set of principles for interaction design focused on five force schemas: *Path restraint, Containment restraint, Counterforce, Attraction, and Compulsion*. We design and describe an initial set of examples that implement these principles using a Leap Motion sensor for gesture tracking and SuperCollider for interactive audio design. Finally, the paper presents a pilot experiment that provides initial insight into how users experience their interaction with the interface, including ratings of the interface's intuitiveness and ability to provide musical inspiration.

Author Keywords
Force dynamics, Image schemas, Leap Motion, Gesture-based instruments, Multimodality, SuperCollider.

CCS Concepts
• Human-centered computing → Interaction design → Interaction design process and methods → User interface design • Applied computing → Sound and music computing

1. INTRODUCTION
Recent technological advances in fine-grained motion tracking have enabled experimentation with new mid-air musical interfaces, where the user interacts with the interface by means of free movement without wearable sensors. The theremin was invented by the Russian physicist Léon Theremin exactly one century before this paper was written, but technologies like Microsoft's Kinect and the Leap Motion controller in particular appear to have reinvigorated the interest in experimental gesture-based interfaces for musical applications, as evidenced by recent literature [1,3,8,15,18,27].

In this paper we use the semantic category – *force dynamics* – as the basis for a theoretical framework to be used in the design of musical interfaces where direct haptic feedback is absent. Furthermore, we present an interface designed to exemplify and evaluate the usefulness of the design framework.

The aim is to explore how force concepts – used by Leonard Talmy [20] to organize meaning in language and subsequently by George Lakoff [11] and Mark Johnson [9] to account for fundamental structures of human imagination (image schemas) that govern thought and language – can serve as a framework to organize meaning in sound and, ultimately, a framework to intuitively interact with sound in mid-air.

While impact force is usually recognized as an important dimension in the design of tactile interfaces for musical interaction, force is a neglected aspect in the design of interfaces with no direct feedback through the tactile senses. Proceeding from the idea that sound is a multimodal phenomenon, we explore how one may design non-haptic interfaces where mid-air gestures activate structural features of tactile force in the user's mind. Such forms of activation are generated through a combination of gestures and sounds based on force schemas.

This study is particular interested in how the bodily *effort* involved in a performance with mid-air instruments can be effectively reflected when combined with sounds designed with specific inherent force characteristics. The goal is to increase *cognitive processing fluency* in such a way that intuitive interaction and meaningful improvisation are possible. When sounds and gestures are designed and combined appropriately, the interface allows for faster processing (cognition is time-pressured, see [7]), constructive stimulation of the user's imagination (unlocks new opportunities that are only imaginable during interaction), and for more precise gestural control.

In order to explore specific sound/gesture combinations we designed an interface using the Leap Motion controller for motion tracking and SuperCollider for sound generation and mapping of gestures to sounds. The design of sounds and gestures was based on five concepts: *Path restraint, Containment restraint, Counterforce, Attraction, and Compulsion.* The choice of these particular force schemas was based on previous studies of force dynamics in music production [21,22,23] and what we found to be a manageable selection of interaction patterns for the interface.

In this paper we thus investigate how design principles grounded in the theory of force dynamics can facilitate designs of intuitive and musically inspiring interfaces based on gesture-tracking technologies such as the Leap Motion. Based on a pilot experiment in which we examined how users experience our interface we provide an initial evaluation of the interface design and discuss possible future directions in force dynamics-based design of mid-air musical interfaces.

2. THEORETICAL FRAMEWORK
Interacting with sound in an improvised performance is a process that involves the mental processing of the heard sound (mind

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external stimuli) and the act of imagining new sounds (mind internal process). Gibbs and Matlock [6] have shown that physical bodily simulation aids both the processing of external stimuli and reasoning about imagined future scenarios. In such cases the body is used as a vehicle to 'off-load' mental computation onto the world. For instance, when experiencing a *tight* sound (see [24] for a discussion of the use of cognitive metaphors in reasoning about sound quality), one may feel the need to squeeze one's hands, and when imagining a *looser* sound to succeed the *tight* sound one may feel the need to *loosen up* the squeezed hands. Also, these hand gestures allow the user to visually 'consult' the interface to reason about the heard sound and to make informed decisions about how to continue the interaction.

Accordingly, imagining and perceiving sound should not be seen as detached cognitive processes, but as integrated elements in the dynamic involvement with a sound interface. Ideally, interfaces should be structurally coupled with the mind's internal cognitive processes in such a way that they 'extend' the cognitive work onto the performance environment – the gesture zone (e.g. the idea of *extended cognition* as presented by Clark and Chalmers [5]).

The interface presented in this paper builds on the idea that our cognitive system is inherently multimodal. When we hear a sound that activates specific mental force schemas, we activate the same neurons as we would activate if experiences with similar force schematic structures were perceived through other senses (see [12]). Similarly, when interacting with a sound interface with no haptic feedback entering through the tactile senses (as opposed to cognitively activated haptic feedback that emerges as a result of appropriate stimulation of other senses), the user may still experience and make sense of the interaction through force schemas learned from previous sensory-motor interactions with the world.

The aim is not to achieve a *representational match* between a specific gesture and the music the gesture generates (e.g. creating *Mickey Mousing* effects where hand movements are used to *represent* different forms of sonic qualities and sequences). Moreover, our approach is different from studies that propose interfaces based on emulations of traditional musical instruments or recording equipment – such as a piano keyboard [8,1,18], drum pads [8], or a mixing console [15].

In the framework we argue for here, both sounds and interactions should be designed and coupled – structurally – through the same set of force schematic mental patterns. The user does not experience these patterns directly, but experiences *through them* – and this is what allows for the activation of sensorimotor experiences that do not *represent* anything particular in the external world, but are experiences that are *governed by* cognitive schemas embodied through previous recurring sensorimotor experiences – in this case, previous force dynamic interactions that lead to embodied force schemas.

Several scholars have presented accounts of force structures in music material – e.g. tonal *tension*, *stability* and *instability*, and *contraction* and *expansion* (see [16,4,13]) – and, further, how these structures are an essential part of the aesthetic appreciation of music (see [17]). Following these studies, we suggest that mid-air interfaces built on force schemas may not only prove more intuitive to use, they may also be perceived as more musically meaningful when venturing beyond imitation of traditional musical interfaces.

3. INTERFACE DESIGN

Inspired by Johnson's theory of force schemas [9], five strategies for the mapping of hand position/movement to musical sound (and vice versa) were devised, focusing on *Path restraint*, *Containment restraint*, *Counterforce*, *Attraction*, and *Compulsion*.

In practice, several of these force schemas are often combined in the perception and conceptualization of sound and music. The schemas are presented here separately for the purpose of clear delineation of the design principles discussed in this paper.

3.1 Path Restraint (Blocking)

Music moves in time. For most people in the English-speaking world, it is common to understand time as something which flows from left to right on a mental timeline – future is on the right side and past on the left [26]. This way of structuring time presumably arises from the direction of our writing system (language and musical notation) [14].

The metaphor of musical movement has been studied extensively by Johnson and Larson [10], who argue that listeners make sense of musical progression as a *force* – grounded in the experience of physical forces – that causes musical material to change from one state to another. Like other forces, musical progression can be blocked by means of a barrier.

An interaction design based on the concept of path restraint implies that the user should be able to introduce a barrier which would continuously interrupt the flow of sound, yet, the sound continues to exert its inherent force on the barrier. Conversely, removing the barrier should enable the music to continue its movement along the force vector from left to right.

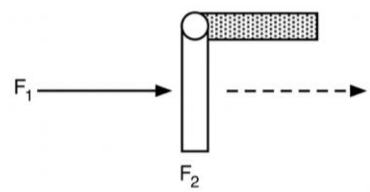

Figure 1. Removal of restraint schema (from [9]).

Figure 1 illustrates how this principle was implemented in Example 1: A musical sequence (F_1) will be in motion before any hands enter the interaction zone. For this example, a sample of pre-recorded sound is played back by means of granular synthesis, a technique which allows for flexible manipulation of audio material. Grains are generated from the recorded sample based on a pointer which moves through the sample such that the perceived playback tempo corresponds to that of the original recording. Placing the right hand (F_2) in the interaction zone stops the progression of the pointer, effectively blocking the musical development. The continuous cycling of similar audio grains illustrates the continued exertion of force against the barrier. When the hand leaves the interaction zone, the pointer resumes normal playback rate due to removal of the barrier.

3.2 Containment Restraint (Compression)

Figure 2 illustrates the containment restraint schema that was used to design Example 2: A generative algorithm produces musical notes distributed within a certain space of possibilities. The size of the space within which the algorithm operates is determined by the distance between the two hands – keeping hands far apart corresponds to a big space, while putting hands closer together compresses the space into a smaller one. The size of the space is illustrated by constraining the algorithm parameters towards weighted randomization with regard to four key parameters: Pitch, rhythm, timbre, and reverberation.

Pitch: An unconstrained space (i.e., no hands) yields a broad range of possible pitches on a pentatonic scale, spanning severaloctaves. Constraining the space narrows the range of possible pitches by limiting the distance between possible scale degrees and operating within one octave only. *Rhythm:* Without constraint, there is a low tempo and a high chance of generating rests in the musical algorithm, leading to a rhythmically sparse soundscape. Constraining the space leads to a higher tempo, fewer rests, and more rapid note envelopes, effectively producing a more intense and rhythmically complex soundscape. *Reverberation:* A big container leads to longer reverberation decay times, and smaller containers lead to shorter decay times. The notes thus appear to reverberate in a physical space which changes corresponding to container size.

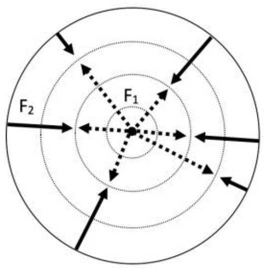

Figure 2. Containment restraint schema.

3.3 Counterforce

Counterforce involves counter movement of a sound with an inherent force tendency that is opposite that of the hand movement. Thus, the movement of hand may either *push* the sound in the opposite direction of its inherent force vector or the hands may *pull* the sound away from its stable position (*stretch*).

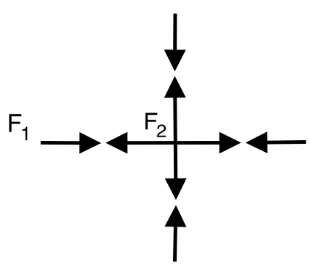

Figure 3. Counterforce schema.

Example 3 implements counterforce (see Figure 3) by establishing an equilibrium in the form of a regular mid-tempo drumming groove which is played at normal playback rate when the right hand is present in the centre of the interaction zone. Moving the hand up or down removes a portion of the frequency spectrum with a low or high pass filter, respectively, whereas moving the hand left or right decreases or increases the playback rate. Toward the extreme horizontal edges of the interaction zone, the playback rate begins to change chaotically, rendering the musical groove increasingly unstable. Removing hands from the interaction zone restores the equilibrium, allowing the counterforce to *push back* and restore the playback rate and frequency spectrum of the original sample.

3.4 Attraction

The attraction schema can be realised as a magnetic force that attracts the sound to an object (a hand) entering the interaction zone. When a hand activates the attraction schema the sound changes gradually until it reaches the position of the hand.

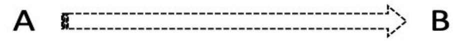

Figure 4. Attraction schema (from [9]).

Example 4 (see Figure 4) implements attraction in the sense that when a hand (B) is detected in the interaction zone, a new sine tone is generated (A) and it moves gradually toward the hand's position, where horizontal position corresponds to the placement of the sound in a stereo field and vertical position corresponds to pitch. When hands leave the space, the force of attraction is no longer present, and the tone descends in pitch before disappearing completely.

3.5 Compulsion

Compulsion involves the movement of something by external force. As opposed to the counterforce force schema, compulsion involves interaction with sounds without inherent force tendencies. When the force exerted on the sound by the hands is removed, the sound will remain in a state of rest.

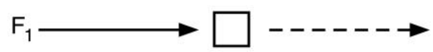

Figure 5. Compulsion schema (from [9]).

Example 5 (see Figure 5) implements compulsion by allowing the user to affect the settings of a simple FM synthesizer by moving his/her right hand around the XY-plane of the interaction zone. Moving the hand along the Y-axis positions the frequency of the *carrier* (i.e. pitch) from low to high. Moving the hand along the X-axis affects *modulator to pitch* ratio when the hand is moved to the right of centre and changes the *modulation index* when the hand is left of centre. Richer and noisier timbres are generated at the far extremes on either side. When the speed of the hand's movement crosses a certain threshold, the pitches begin to shift randomly, and the timbre becomes increasingly rough. This latter aspect of the sound design is meant to provide sonic feedback when the hand is in motion, i.e. a form of sonic friction.

4. TECHNICAL IMPLEMENTATION

As a well-known piece of hardware within the NIME community, the Leap Motion was selected for this study as an accessible way to develop a prototype interface for tracking hand motion and position. Originally developed for virtual reality applications, the Leap Motion hardware was released in 2012 and has subsequently been used in many experimental interfaces for computer music. The sensor tracks the position of a user's arms, hands, and fingers in 3D space by means of infrared cameras. In this way, impressive precision and low latency is achieved (see [18,27] for further discussions of the controller and its limitations).

The interactive sound design for the examples was developed in SuperCollider, a free and open source platform for audio synthesis and algorithmic composition [19]. Built for interactivity with a strong library of generative algorithms and a highly capable audio synthesis and signal processing engine [25], SuperCollider was a fruitful platform for this project.

As an interface between the Leap Motion controller and SuperCollider, a small JavaScript application was developed in order to pull data from the sensor using the Leap Motion JavaScript API and communicate with SuperCollider using the OSC protocol. This approach has the advantage of working natively in a web browser, which afforded rapid prototyping of a simple graphical interface by means of which users could switch between examples and get some minimal feedback on the sensor's ability to 'see' their hands.

Some previous studies of interface design involving the Leap Motion controller employ different imaginative forms of visual feedback [3,1]. Since the intention of the present study was to test how interface intuitiveness can be achieved primarily through *auditory* rather than *visual* feedback, we did not provide visual feedback about the position or movement of the user's hands. Visual feedback was used only to indicate whether or not the controller was able to "see" the user's hands, in the form of an on-screen hand symbol which lights up when the hand is registered as present within the interaction zone (see figure 6 and 7).

Figure 6. Example 1 is activated. Hand is not present in the interaction zone.

Figure 7. Example 1 is activated. Hand is present.

We decided to highlight the presence of hands in the interaction zone with visual feedback to deal with the instability of the sensor toward the extreme edges of the interaction zone, which in initial tests proved confusing for users with no previous experience with the controller. Since the examples differed regarding the number of hands the user should use to navigate the interface, simple text instructions for each example in the graphical user interface were provided at the bottom of the user interface screen.

5. EVALUATION

A pilot study was conducted with 11 participants (all male – eight current musicology students and three former musicology students) to provide an initial indication of intuitiveness and general evaluation of the user experience.

5.1 Procedure

Each participant was given a brief introduction to the interface and was then allotted five minutes to play with the interface without researcher interference. Participants were then asked to fill out a survey which involved rating each example on whether the example was intuitive to use and whether the example was musically inspiring. Ratings were given on a five-level Likert scale ranging from "Strongly disagree" to "Strongly agree". Subsequently, participants were asked to evaluate their general experience of using the interface by checking five items on a list of 10 descriptors (six positive and four negative descriptors) subtracted from the Microsoft Desirability Toolkit [2]. Throughout the experiment, and while filling in the survey, participants were able to switch freely between the five examples to explore the interaction possibilities of the interface. The sessions were recorded on video. After each session, a short debriefing was conducted during which participants were invited to express their impressions in their own words.

5.2 Results and discussion

Generally, participants found much to praise in the presented examples of interaction patterns and corresponding sounds. In the evaluation session participants reported the interface to be *captivating, entertaining, inspiring, and intuitive* (figure 10).

Figure 10, Word cloud for general descriptors of the interface.

The analysis of the video-recorded sessions supports the reported viewpoint that the interface was entertaining and inspiring. Still, none of the participants operated all five examples as intended inside the allotted five minutes.

Example 1 (*Path restraint*) had – from a design perspective – the simplest interaction pattern as it only responded to whether the right hand was present or not. Some participants reported that the interaction pattern reminded them of DJ'ing (scratching). This association is consistent with the design principle in example 1 – to interrupt the flow of music – and it explains why all participants blocked the flow of music by placing their fingers on a virtual surface (palm of right hand facing down) rather than blocking the flow of music by using the hand as a barrier (palm of right hand facing left). Others, however, found this example unintuitive – presumably, because the interaction was too simple compared to their expectations – nothing happened when they moved the right hand forth and back within the interaction zone.

Example 2 (*Containment restraint*) was rated as both the least intuitive and the least musically inspiring among the five examples. Most participants attempted to operate the interface example with one hand at a time (despite the instructions displayed on the screen to use both hands) and those who used both hands simultaneously primarily attempted to adjust different parameters with each hand. Two participants appear to move their hands together and apart to control the sound after having played around with this specific example for more than 90 seconds. This suggests that this example – where the coordination of hand movements is essential for the working of the interface – requires more time to learn.

Example 3 (*Counterforce*) and example 4 (*Attraction*) were reported as the most intuitive and most musically inspiring examples.

The video shows that most participants acquire some control with the interface examples and start to make music within 30 seconds or less. However, in both cases most participants only operate the examples in one dimension (the vertical dimension).

In comparison to example 3 and 4, fewer participants found example 5 (*Compulsion*) to be intuitive or musically inspiring, yet, all participants appear to adjust the sound on both the X and Y-axes within approximately 30 seconds.

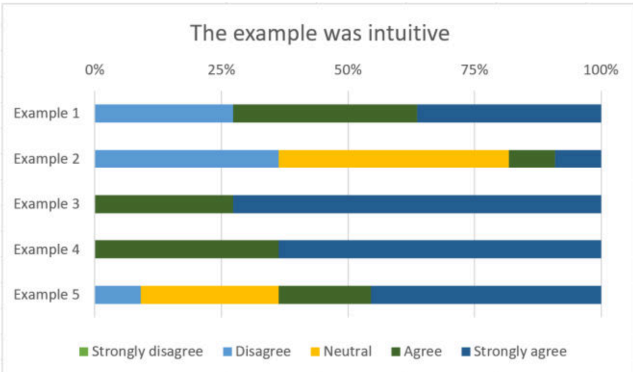

Figure 8. Survey results: "The example was intuitive".

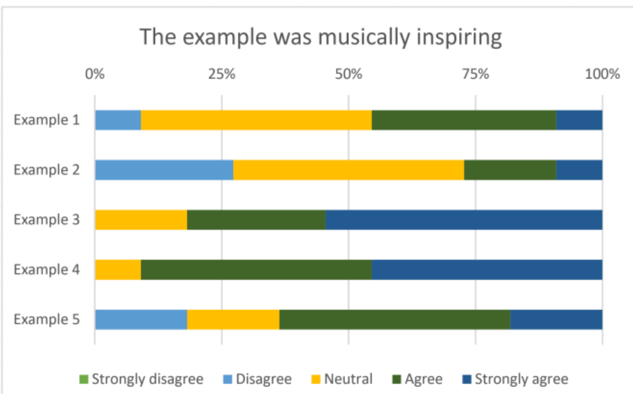

Figure 9. Survey results: "The example was musically inspiring".

During debriefing, five participants reported that they experienced latency in some of the examples (e.g. in example 4) or that the interface occasionally did not respond properly to the hand movements. This perceived latency/unresponsiveness of the system (the technical latency of the system is only a few milliseconds and unlikely to be perceivable) suggests that the instrument's gradual changes to timbral and spatial qualities in some cases clashes with the user's expectations – expectations presumably embodied in previous experiences with interfaces built on a direct representational match between movement and sound or other interfaces/instruments with instant response sounds.

6. CONCLUSION AND PERSPECTIVES

In this paper we argued that force dynamics may serve as a meaningful design principle for more intuitive and inspiring mid-air interfaces for musical expression. Users' self-reported assessments of intuitiveness based on five minutes of interaction with the interface can only provide limited insight into the general usability of the particular interface developed here. Based on the findings in the pilot study, however, we suggest that the proposed design principles allow for the development of interfaces which function as cognitive extensions in such a way that the user can 'consult' the interface in a meaningful way to make informed decisions about future actions.

To make detailed observations and user ratings of the five different interaction patterns, this study tested each pattern separately. The pilot test shows that examples built on the simplest and most complex interaction patterns (*Path restraint* and *Containment restraint*) were found to be the least intuitive and musically inspiring. The remaining three examples – where the user interacts with the sound by moving one hand at a time on the X and Y-axes – were more intuitive and inspiring. Interestingly, example 4 *(Attraction*), where some participants experienced latency, was rated as the most musically inspiring while example 1 (*Path restraint*) was intuitive yet relatively uninspiring.

We suggest that the influence of visual cues and user expectations needs to be addressed further in future experiments. While the auditory material may evoke force dynamic patterns in the user's mind, there is, in fact, no visual and physical restraint in free air. This may lead to cognitive dissonance between the basic meaning of the force schemas and the perceived nature of the physical material in the interaction zone (air), resulting in a lack of perceived intuitiveness.

It is assumed that a stronger link between abstract metaphorical thinking (how the user makes sense of the timbral and rhythmic variations in the auditory material) and concrete actions (the hand gestures) will make the interface both more intuitive and musically meaningful. For this reason, we plan to experiment with different sound designs and to introduce perceptual stimuli from other modalities, e.g., implement visual cues to support the basic force schemas, in future versions of the interface. Since multiple force schemas are often combined in everyday cognition, we also plan to test how different combinations of force patterns in the same interaction zone can strengthen the aforementioned link. Combining path restraint and compulsion such that the user can restrain the music's inherent motion while changing other musical aspects through hand gestures, for instance, could draw upon the relatively high intuitiveness of example 1 and extend the interactive and sonic possibilities.

Future research into the effect of user expectations on perceived intuitiveness of mid-air interfaces could address the relationship between the user's background, expectations, and his/her experience of the interface. The participants in this study shared a background in musicology, but including participants with other backgrounds could provide valuable insight into the usability and potential applications of mid-air musical interfaces across contexts.

7. ACKNOWLEDGMENTS

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The software we developed for this project is free and open source, available at https://github.com/sparkletop/forces. The software may change in the future, but the setup that was used for the present study can be replicated using version 0.2, which is available at https://github.com/sparkletop/forces/releases/tag/v0.2.

8. ETHICAL STANDARDS

All participants were informed about the purpose of the study and consented to participate. Data storage and processing complies with EU's General Data Protection Regulations (GDPR).

9. REFERENCES

[1] N. Alessandro, J. Tilmanne, A. Moreau, and A. Puleo. AirPiano: A Multi-Touch Keyboard with Hovering Control. *Proceedings of NIME'15*, 2015, 255–58.

[2] J. Benedek and T. Miner. Measuring Desirability: New Methods for Evaluating Desirability in a Usability Lab Setting. *Proceedings of UPA 2002 Conference,* 2010.

[3] F. Berthaut, C. Arslan, and L. Grisoni. Revgest: Augmenting Gestural Musical Instruments with Revealed Virtual Objects. *Proceedings of NIME'17*, 2017, 180–85.

[4] C. Brower. A Cognitive Theory of Musical Meaning. *Journal of Music Theory* 44 (2), 2000, 323–379.

[5] A. Clark and D. J. Chalmers. The Extended Mind. In *The Extended Mind,* edited by R. Menary. MIT Press, Cambridge, Massachusetts, 2010, 27–42.

[6] R. W. Gibbs and T. Matlock. Metaphor, Imagination, and Simulation. In *The Cambridge Handbook of Metaphor and Thought*, edited by R. W. Gibbs. Cambridge University Press, Cambridge, 2008, 161–176.

[7] M. Grimshaw and T. Garner. *Sonic Virtuality – Sound as Emergent Perception*. Oxford University Press, Oxford and New York, 2015.

[8] J. Han and N. Gold. Lessons Learned in Exploring the Leap Motion Sensor for Gesture-Based Instrument Design. *Proceedings of NIME'14*, 2014, 371–74.

[9] M. Johnson. *The Body in the Mind: The Bodily Basis of Meaning, Imagination, and Reason*. The University of Chicago Press, Chicago and London, 1987.

[10] M. Johnson and S. Larson. "Something in the Way She Moves": Metaphors of Musical Motion. *Metaphor & Symbol* 18 (2), 2003, 63-84.

[11] G. Lakoff. Women, Fire and Dangerous Things: What Categories Reveal about the Mind. The University of Chicago Press, Chicago and London, 1987.

[12] G. Lakoff. The Neural Theory of Metaphor. In *Cambridge Handbook of Metaphor and Thought*, edited by R. Gibbs. Cambridge University Press, Cambridge, 2008, 17-38.

[13] S. Larson. *Musical Forces: Motion, Metaphor, and Meaning in Music*. Indiana University Press, Bloomington, 2012.

[14] M. Oullet, J. Santiago, Z. Israeli, and S. Gabay. Is the Future the Right Time? *Experimental Psychology* 57 (4), 2010, 308–314. DOI: 10.1027/1618-3169/a000036

[15] J. Ratcliffe. Hand and Finger Motion-Controlled Audio Mixing Interface. *Proceedings of NIME'14*, 2014, 136–39.

[16] J. Saslaw. Forces, Containers, and Paths: The Role of Body-Derived Image Schemas in the Conceptualization of Music. *Journal of Music Theory* 40 (2), 1996, 217–243.

[17] R. Scruton. *The Aesthetics of Music*. Clarendon Press, Oxford, 1999.

[18] E. S. Silva., J. Abreu, J. H. de Almeida, V. Teichrieb, and G.r L. Ramalho. A Preliminary Evaluation of the Leap Motion Sensor as Controller of New Digital Musical Instruments. *Proceedings of the 14th Brazilian Symposium on Computer Music*. Brasília: Escola de Música de Brasília, 2013, 59–70.

[19] SuperCollider. https://supercollider.github.io/, accessed on January 21, 2020.

[20] L. Talmy. Force Dynamics in Language and Thought. *The Parasession on Causatives and Agentivity at the Twenty-First Regional Meeting*, Chicago, Illinois, Chicago Linguistic Society, 1985.

[21] M. Walther-Hansen. The Force Dynamic Structure of the Phonographic Container: How Sound Engineers Conceptualise the 'Inside' of the Mix. *Journal of Music and Meaning,* 12, 2014.

[22] M. Walther-Hansen. Balancing Audio: Towards a Cognitive Structure of Sound Interaction in Music Production. In *Music, mind, and embodiment*, edited by R. Kronland-Martinet, M. Aramaki and S. Ystad. Springer, 2016, 228-242.

[23] M. Walther-Hansen. New and Old User Interface Metaphors in Music Production. *Journal of the Art of Record Production* 11, 2017.

[24] M. Walther-Hansen. 2020. *Making Sense of Recordings*. Oxford University Press.

[25] S. Wilson and J. D'Escriván. Composition with SuperCollider. *The SuperCollider Book*, edited by S. Wilson, D. Cottle, and N. Collins, MIT Press, 2011, 81–104.

[26] B. Winter and T. Matlock. Primary Metaphors are both Cultural and Embodied. In *Metaphor – Embodied Cognition and Discourse* edited by B. Hampe. Cambridge University Press, Cambridge and New York, 2017, 99–116.

[27] J. C. Wu, Y. Zhang, and M. J. Wright. Towards Robust Tracking with an Unreliable Motion Sensor Using Machine Learning. *Proceedings of NIME'17*, 2017, 42–47.